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CRITICAL POINTS: INTERACTIONS BETWEEN ON –FARM IRRIGATION SYSTEMS AND WATER DISTRIBUTION NETWORK. APPLICATION IN BEMBEZAR M.D., SPAIN

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Que el Trabajo de Fin de Máster titulado "CRITICAL POINTS: INTERACTIONS BETWEEN ON –FARM IRRIGATION SYSTEMS AND WATER DISTRIBUTION NETWORK. APPLICATION IN BEMBEZAR M.D., SPAIN", ha sido realizado por D. Rafael González Perea, bajo su dirección, para la obtención del título de Máster Universitario en Proyectos y Gestión de Plantas Agroindustriales por la Universidad de Córdoba, es un trabajo original e inédito y reúne los requisitos necesarios para su exposición y defensa, en la modalidad de artículo científico.

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CRITICAL POINTS: INTERACTIONS BETWEEN ON –FARM IRRIGATION SYSTEMS AND WATER DISTRIBUTION NETWORK.

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ABSTRACT

In this work, a new model useful to analyze interactions between the on-farm irrigation system supplied by critical points and the water supply network management is developed. The model evaluates the impacts of changes in the pressure head and demand simultaneity on the irrigation systems and evaluates the emitters' discharge and uniformity. Also, the potential reductions in yield due to lower uniformity are evaluated.

The methodology is applied in Bembézar Irrigation District (Southern Spain). Results showed that the additional cost required for giving maximum pressure in the critical point does not offset the increase in yield. Hence, an increment from 91.7 % to 92.1 % in yield in the critical field would represent increases in energy consumption from 0.15 kWh m^{-3} to 0.17 kWh m^{-3}. Also, the unit energy cost could be reduced in up to 0.11 kWh m^{-3} not implying significant reductions in yield. The importance of a good election of emitters in the critical fields is also evaluated.

KEYWORDS: energy savings, pressurized irrigation, hydraulic modelling

INTRODUCTION

With the aim of increasing the irrigation efficiency and give farmers the maximum flexibility, many water distribution networks have been designed to supply pressurized water and organized on-demand. Thus, the obsolete open-channels hydraulic infrastructures have been replaced by new pressurized networks (Plusquellec 2009). This change increases the conveyance efficiency reducing water losses throughout the system. In addition, farmers get a much greater degree of flexibility allowing the use of more efficient on-farm irrigation systems such as trickle or sprinkler and therefore increasing uniformity and irrigation frequency (Rodríguez Díaz *et al.* 2007a; Lamaddalena *et al.* 2007; Pérez Urrestarazu *et al.* 2009).

However, these pressurized networks have significantly increased the energy demand. For example, in Spain, where an ambitious modernization plan of irrigation schemes has been carried out (MAPA 2001), Corominas (2010) reported than while water use has been reduced in 21% from 1950 to 2007, the energy demand was increased in 657% in this period. For this reason, several authors have highlighted the necessity of reducing the energy requirements, improving the performance of both the water distribution and on-farm irrigation systems (ITRC 2005; Moreno et al. 2007, 2009; Pulido-Calvo *et al.* 2003; Abadia *et al.* 2008; Vieira and Ramos 2009; Daccache *et al.* 2010).

There are several strategies for energy optimization in pressurized irrigation networks. Network's sectoring, where hydrants with similar energy requirements are grouped, is one of the most effective measures (Rodríguez Díaz *et al*., 2009; Carrillo Cobo *et al*., 2011, Navarro Navajas, 2012). Another energy saving measure is the control of critical points, which are hydrants with high energy requirements. Rodríguez Díaz *et al.* (2012) developed the WECP (Water and Energy optimization by Critical Point control) algorithm for detecting critical points in pressurized irrigation networks. It was applied in two pressurized irrigation networks in Southern. The results showed that potential energy savings around 10% and 30% were possible in each district when the theoretical irrigation requirements were modeled. However, the WECP offered energy saving measures at distribution network level, not considering the possible on-farm irrigation implications in the fields supplied by the critical hydrant. Reductions in the pressure head at the pumping station may drastically affect the distribution uniformity of the on-farm irrigation system and therefore have significant negative impacts on yields (Smajstrla *et al,*. 1990).

In water distribution systems that operate on demand, flows in pipes are subjected to fluctuations according to the simultaneity of the demand (Rodríguez Díaz *et al.*, 2007). However, when the water demand is high, the energy losses in pipes are increased and the pressure on hydrants are reduced. Related to this, several modeling approaches have been developed to assess the performance of on-demand systems. For example, the indexed characteristic curve approach (CTGREF 1979; Bethery *et al.* 1981) evaluates the overall performance of the distribution system while the AKLA model (Lamaddalena and Sagardoy 2000) provides more specific information about the percentage of hydrants with sub-optimal performance, their position and the magnitude of their pressure deficit. In the Apulia irrigation district (Italy), the critical hydrant showed a potential pressure variation ranging between 64 and 24 m when the upstream system discharge fluctuates between 600 and 1,200 L s^{-1}. These fluctuations had important impacts on the on-farm irrigation system performance (Daccache *et al.*, 2010).

In this work, a useful methodology to detect the impacts of the pumping station's management on the on-farm irrigation system is developed and applied to a real irrigation network in Southern Spain. Thus pressure head changes in the pumping station affect the pressure in critical points and consequently the distribution uniformity of their associated irrigation systems. The impact of these pressure variations are evaluated in terms of yield.

METHODOLOGY

Study area

The M. D. Bembézar Irrigation District (Southern Spain) has a total irrigated area of 11,950 ha (Figure 1). The climate is Mediterranean with an annual average rainfall of 604 mm and an average temperature of 17.7 ºC, with July being the hottest month (36.2 ºC of mean temperature). Under these circumstances the average reference evapotranspiration is over 1,200 mm. The main crops in the irrigation district are: mostly citrus, cotton, maize and fruit trees.

The water is conveyed from three different reservoirs (Bembézar, 342 Mm^3; Retortillo, 61 Mm^3; José Torán, 101 Mm^3) through a main channel of 40 km length and 12 m^3 s^{-1} of delivery capacity. Then, eleven pumping stations operate along the main channel to supply water to each sector. The network was designed to supply 1.2 L $s^{-1}ha^{-1}$ on-demand at a minimum operation pressure at hydrant level of 35 m. Drip irrigation is the most common irrigation system. Sector VII, that covers a total irrigated area of 935 ha (Figure 2), is analyzed in this work.

Critical field

The most critical point was identified in sector VII. Thus, the field that is supplied by the most critical hydrant (critical field) is devoted to maize and has an irrigated area of

4.7 ha. A pressure regulation valve is placed downstream of the hydrant (which reduces the pressure to 35 m) as well as a filter battery, whose friction losses were estimated in 7 m.

The irrigation system is trickle, with spacing of a=0.5 m and b=1.8 m (axb; spacing between emitters x spacing between laterals). The emitters' nominal flow is 2.2 L h^{-1} and the pressure-compensation range varies from 10 to 40 m. The emitters' flow-pressure equation is:

$$q = \alpha \, h^{x} \tag{1}$$

Where q is the flow rate (L h^{-1}), h is the pressure head (m), α is the discharge coefficient (L h^{-1} m^{-x}) and x is the pressure exponent. In this work, x=0.04 and α=1.79 L h^{-1} $m^{-0.04}$.

Problem formulation

Initially, the critical point detection is carried out using the algorithm WECP (Rodríguez Díaz *et al.*, 2012). This algorithm detects critical points (most energy demanding hydrants) through several thousands of network operation simulations under randomly generated loading conditions.

Then, a new model for analyzing the impacts of the network's management on critical fields was developed (Figure 3).

The model simulated the network's behaviour during the peak water demand month for different pressure heads. Furthermore, the model linked the simultaneity of the water demand and the pressure at hydrants, considering the probability of open or closed hydrant as described in Carrillo Cobo *et al.* (2011). Thus, the theoretical daily average irrigation needs in the irrigation district per month and hydrant (mm) were estimated as described in FAO 56 (Allen *et al.*, 1998). This information was transformed into irrigation needs in the peak water demand period, *IN* (L ha^{-1} day^{-1}), and was used to estimate the daily irrigation time required in the peak month, t_n (hours), per hydrant (n):

$$t_n = \frac{1}{3600} \cdot \frac{IN}{q_{max}} \tag{2}$$

being q_{max} was the maximum flow allowed per hydrant (L s^{-1} ha^{-1}). Then, the open outlet probability in the month of maximum demand (Clément, 1966), p_n, was calculated for each hydrant (n) as follows:

$$p_n = \frac{t_n}{t_a} \tag{3}$$

Where t_a was the daily irrigation availability time (24 hours in on-demand systems).

Finally, it analyzed the impacts of changes in pressure head on the on-farm irrigation system's behaviour.

The developed model was implemented in MATLAB, using the hydraulic simulator EPANET (integrated through its dynamic library, DLL) (Rossman, 2000).

<u>Network´s hydraulic behaviour for different pressure heads at the pumping station</u>

Initially the model fixed the pressure head at the pumping station, $h_{ps,i}$, then j random demand patterns, RDP, (set of open/close hydrants) were generated. A random demand pattern was generated for every iteration, j. Open hydrant probability value, p_n, smaller or equal than random numbers generated with random demand patterns, identify the k_j sets of open hydrants, otherwise hydrants are considered closed with no water demand. The demanded flow for every open hydrant was estimated as follow:

$$q_n = q_{max} \cdot S_n \tag{4}$$

Where S_n was the irrigated area supplied by hydrant n. Then the network behaviour under each random demand pattern and pressure head value, $h_{ps,i}$, was analyzed using the EPANET's engine.

All this process begins with a maximum pressure head ($h_{pi,max}$) and decreases in each iteration (i) in Δh. Thus, the effects that the pressure head at the pumping station and the simultaneity of the demand have in the pressure of the critical hydrant were analyzed. Limits of i and Δh depends on emitters installed on the field.

Power and energy requirements

The demanded flow in the pumping station, Q_{Tij} in (m^3 s^{-1}) was determined for each demand patterns. For each pair of demanded flow and pressure head, (loading condition) the power requirements, P_{ij} (kW), at the pumping station were calculated according to the following equation:

$$P_{ij} = \frac{\gamma * Q_{Tij} * h_{ph,i}}{\eta} \quad (5)$$

Where γ is the water specific weight (9.8 kN m^{-3}) and η the pumping system efficiency (in this work 0.8 pumping efficiency has been assumed). Then, the energy consumption in kWh per working day for each loading condition was estimated as follows:

$$E_{ij} = P_{ij} * t_n \quad (6)$$

Pumped flow, pressure head, power and energy for each loading conditions were averaged for the peak month;

Hydraulic behaviour of the critical field

Taking as input the pressure in the critical hydrant (h_c), the hydraulic behaviour of the emitters in the critical field was analyzed and the possible reductions in yield due to variations the distribution uniformity were estimated. Thus, the on-farm irrigation system was also modelled in EPANET and simulated.

Then, the pressure and irrigation depth distribution were calculated for all the emitters in the critical field. The descriptive statistics (mean, $\overline{H_e}$; standard deviation, σ_e; and coefficient of variation, CV_e) for the emitters' irrigation depth were estimated. Considering that there are no runoff losses, the mean depth coincides with the total gross applied depth, H_g. The total number of emitters in the critical field was calculated according to equation 7.

$$e = \frac{S_n}{a \cdot b} \tag{7}$$

<u>On-farm irrigation system evaluation</u>

The on farm distribution uniformity was evaluated using the ratio (H_g/H_r). This relationship was calculated according to Alabanda (2001):

$$\frac{H_g}{H_r} = \frac{1-C_d}{IE} \tag{8}$$

Where IE is the irrigation efficiency. It is the ratio of the net irrigation requirements, (H_n) (mm) and the total gross applied depth, H_g (mm); C_d is the deficit coefficient, that is the ratio of the water deficit (H_r–H_n), and the theoretical irrigation requirements, (H_r). These coefficients were described by Losada (1996) and calculated according to equations 9, 10 and 11.

$$IE = \frac{\overline{H_e} - \frac{1}{2} * \frac{(\overline{H_e} + \sqrt{3}\sigma_e)^2 - {H_r}^2}{2\sqrt{3}\sigma_e} + f * H_r}{\overline{H_e}} \tag{9}$$

Where f was the fraction of the field which do not suffer water deficit:

$$f = \frac{\overline{H_e} + \sqrt{3}\,\sigma_e - H_r}{2\sqrt{3}\sigma_e} \tag{10}$$

$$C_d = \frac{(1-f)*H_r - \overline{H_e} + \frac{1}{2}*\frac{(\overline{H_e}+\sqrt{3}\sigma_e)^2 - {H_r}^2}{2\sqrt{3}\sigma_e}}{H_r} \tag{11}$$

Additionally, the distribution uniformity of the flow is also evaluated, using the Christiansen's coefficient (CU_c):

$$CU_c = 100 * \left[1 - \frac{\sum_{i=1}^{e} |H_i - \overline{H_e}|}{e\,H_g}\right] \tag{12}$$

Where H_i was the applied irrigation depth for every emitter (mm), which is one of the EPANET's outputs.

Crop yield estimation

The irrigation uniformity and yield reductions were linked using the following equation (Allen *et al.*, 2006):

$$1 - \frac{Y}{Y_{max}} = K_y\left(1 - \frac{H_g}{H_r}\right) \tag{13}$$

Where Y was the actual yield of the crop (kg ha^{-1}); Y_{max} was the maximum yield without water stress (kg ha^{-1}); K_y was the yield response factor.

The farmer's benefit, in € ha^{-1}, was calculated according to equation 14. The crop production costs are independent of the network's management. Thus, the profit was calculated taking into account only water costs, which was calculated from the energy consumption per unit of irrigation water supplied, in kWh m^{-3} and the energy price, in € kWh^{-1}.

$$Profit = (Y_c \cdot P_c) - C_w \tag{14}$$

Where Y_c was the yield of the crop (kg ha^{-1}); P_c was the market price of the agricultural production (€ kg^{-1}) and C_w was the water cost (€ ha^{-1}).

Alternative management scenarios

The analysis of alternative emitters can be easily carried out changing the emitter's equations (equation 1). The influence of the irrigation system in the critical field can be easily evaluated just using different pressure-flow equations.

Thus, three alternative emitters according to equations 15 (Scenario A) and 16 (Scenario B) were tested.

$$q = 0.73\, h^{0.47} \quad (15)$$

$$q = 0.64\, h^{0.53} \quad (16)$$

Where q in (L h^{-1}) and h pressure head in (m).

RESULTS AND DISCUSSION

The model simulated the behaviour of the network during the peak month (June). $h_{ps,\,max}$ was set to 55 m and Δh was 2 m. The i parameter ranged from 1 to 16. The number of iterations j was set to 2,250.

Water demand and pressure in pumping station

As the water distribution network is operated on demand, the supplied flows are subjected to fluctuations in the number of hydrants which are simultaneously open. Thus, flows ranged from 350 L s^{-1} (when low simultaneity occurs) to 840 L s^{-1} when most of the hydrants were open.

The influence of the simultaneity of the demand (set of open hydrants) in the pressure at hydrant level was very small. A linear relationship between the pressure head ($h_{ps,i}$) and the pressure at the critical hydrant (h_c) have been identified ($h_c = h_{ps}$ -13.864; r^2=1). Due to the design criteria of the network (100% of simultaneity), the energy losses are not too high even when all hydrants irrigate because pipes were sized for the maximum demand. Wider ranges of pressure variation at hydrant can be expected for other networks where some pipes may be undersized.

Irrigation uniformity in the critical field

The irrigation uniformity decreases when the pressure in the critical field drops below 35 m. Table 1 relates the average of the pressures for all the iterations at the critical hydrant ($\overline{h_c}$) and the pressure head at the pumping station with the CV_e and the CU_c in the critical field.

While the pressure in the critical hydrant was above 35 m the pressure regulator was active. Then the maximum value of CU_c is 99.82 %. and when the pressure at hydrant is less than 35 m, the CU_c is slightly reduced from 99.82% to 98.03%. As, the pressure-compensating range of the emitters is from 10 to 40 m, the CU_c and yield do not vary significantly in this range. Below 10 m of pressure, the emitters are out of their pressure compensating range and significant reductions in flows are expected.

The spatial distribution of pressures and flows in the critical field is shown in Figure 4 for three different pressure heads. When the pressure head at the pumping station is 53 m, the pressure in the critical hydrant is 39.24 m (Table 1) and the pressure regulator was active. As a consequence, all the emitters received adequate pressure, there are minimum variations in the pressure distribution due to the topography of the field, but all emitters operate within the pressure compensating range. In relation to the flow distribution, all emitters supply the nominal flow (Figure 4a).

In Figure 4b the spatial pressure distribution for a pressure head at the pumping station of 43 m is showed. In this case, the pressure in the critical hydrant was 29.25 m (Table 1) so the pressure regulator was inactive. However, all emitters operated within the auto-compensating range (10-40 m) and the supplied flows are similar to those found in Figure 4a (nominal flow). When the pressure head drops to 25 m, the pressure at hydrant is 11.25 m and most of the emitters stop working properly, as they operate bellow 10 m.

Figure 5 shows the evolution of the coefficient of how variation of the emitters at different pressures in the critical hydrant. When the pressure is higher than 35 m, the CV remains constant thanks to the pressure regulator. When the pressure is less than 35 m, the pressure regulator does not work and the CV_e is increased. Since the emitters are pressure compensating, the CV_e did not change much while pressure was within of the pressure-compensation range. Given that the emitters are pressure compensating, big changes in the CV_e are not expected (it changes from 0.22% to 1.27%).

Yield in the critical field

The total number of emitters in the critical field is estimated from equation 7. In this case, the critical field had 20,175 emitters. Due to the large number of emitters, the calculation time required for the critical field was too high. Thus, the field was skeletonized, eliminating 2 out of 3 branches and replaced by equivalent consumption points. Therefore, the skeletonized field had 6,725 emitters.

The irrigation time required in the peak month (t_n) was calculated from equation 2 and it was a constant value of 14.6 hour.

Even when the pressure at hydrant is 35 m, the yield is 92.1% of the maximum potential yield (Table 1). According to the manufacturer, the emitter´s nominal flow was 2.2 L h^{-1} and the irrigation events are scheduled according to this value. But in the hydraulic simulations this nominal flow was not reached at any time even when the pressure was adequate. Furthermore, the emitters were not fully compensating because the pressure exponent of the emitter was not zero.

When the pressure at hydrant drops to 11.25 m, the pressure of many emitters is lower than the minimum limit of admissible pressure and the yield is reduced to 82.3% of the maximum potential yield, because the water discharge in those emitters is smaller and therefore the crop receives less water than the theoretical requirements. The spatial distribution in this case is shown in Figure 4c. Figure 6 shows the relationship between applied water and the theoretical irrigation requirements for each pressure at hydrant level. When the pressure is reduced, the ratio $(\frac{H_g}{H_r})$ is reduced too and, therefore, less water is available to the crop.

Energy use

The relationship between energy consumption per cubic meter in the peak month and the pressure head at the pumping station is shown in Table 1. The current operation of the pumping station is 45 m which provides around 32 m of pressure in the critical hydrant. The average unit energy consumption in the current management is 0.15 kWh m^{-3}. In this case, the yield losses are a bit more than 8%. However, if the pressure head were reduced to 33 m, the production yield losses would be slightly smaller (12 %) but the unit energy consumption would be 0.11 kWh m^{-3} for all the water supplied by the pumping station in June. The system can even operate bellow this pressure.

The current water consumption in June was 972,486 m^3 and, assuming an unit energy cost of 0.10 € kWh^{-1}, the energy cost, in the current condition, is 14,587 € (assuming similar irrigation scheduling for the whole irrigation season). If the system operated under 33 m at the pumping station, the energy costs would be 10,697 €, which represents 27 % of economical savings for the Irrigation District in the peak month. This operation option does not involve significant losses in yield in the critical field. This fact means that the yield losses that may occur in the critical field are much lower than the increase in energy costs needed to give more pressure at the critical hydrant. Finally, if the pressure at the pumping station was 49 m, the critical hydrant would receive the adequate pressure (35 m) and the energy costs would be 16,532 €. In this case, the maximum yield is achieved (92.1 %).

According to the annual statistics of agriculture department of Andalucía (Spain) (Agriculture department of Andalucía, 2009), the maize had an average yield of 10,348 kg ha^{-1}, average market price of 0.14 € kg^{-1}. The cost of water for the critical field in June is shown in Table 2. Thus, profits of the critical field are 1,035.81 € ha^{-1}, for the current pressure at the pumping station. If the pressure head was 49 m, profits in the critical field decrease to 1,023.13 € ha^{-1}, i.e. the increase in the agricultural production value is less than the increase in the water cost. On the other hand, if the network operated at 33 m at the pumping station, profits in the critical field would be 1,080.00 € ha^{-1}, 25.90 € ha^{-1} more than the current condition (Table 2).

Sensitivity to other emitters

The effects of different irrigation emitters were tested in the model. Thus, two scenarios A and B were analyzed, with flow – pressure curves shown in equations 15 and 16 respectively.

Scenario A and B

The emitters in the scenarios A and B are not pressure compensating and therefore more changes in flow are expected due to variations in pressure. The nominal flow (2.2 L h^{-1}) in the emitter is achieved when the pressure at critical hydrant is 19.25 m and at the pumping station is 33 m.

The model was run for these two scenarios. The CV_e in the Scenario B varied from 8.13% for the maximum simulated pressure (33 m) to 47.01% for minimal pressure head (23 m). For the same range of pressure, the CV_e in scenario B changes from 9.16% to 46.85% (Table 3). The CU_c ranged from 93.51% to 62.49% in scenario A and from 92.69% to 62.62% in scenario B. The sensitivity to changes in pressure head is higher than in the currents emitters (equation 1) and therefore they do not represent the best option for the critical field.

When yields are analyzed, both emitters achieve 100% when the pressure head is 33 m, it drops rapidly when the pressure is reduced (37.2% and 34.6% when the pressure head drops to 23 m) (Figure 9). The closer relationship between flow and pressure lead to a poorer uniformity and therefore the higher spatial variability in the emitters' discharge (Figure 7). Also, contrarily to what happened when the current emitters where modelled, the ratio of applied and theoretical depths is very sensitive to pressure changes (Figure 8).

CONCLUSIONS

In this work, a new methodology to simulate the interactions between on-demand water distribution systems and irrigation performance in critical points has been developed and applied in the BMD irrigation district.

On-demand irrigation implies a significant expenditure in energy which is even higher when some critical points are responsible for an large percentages of the total pressure head. Thus, it is extremely necessary an effective management of the critical points that enhance the overall efficiency of the irrigation infrastructure with minimum costs. However, detailed analysis, at water distribution and on-farm irrigation systems levels, are needed before the adoption of improvement measures.

In this particular case, results showed that the additional cost required for giving maximum pressure in the critical point does not offset the increase in yield. Here, an increment from 91.7 % to 92.1 % in yield in the critical field would represent increments in energy consumption from 0.15 kWh m^{-3} to 0.17 kWh m^{-3} and therefore an increment of 8.5 % in the energy consumption in the peak demand month. This network management implies an increase in the cost of water in the critical field of 36.85 € ha^{-1} and therefore a reduction in profits of 30.97 € ha^{-1}.

On the other hand, the unit energy cost could be reduced in up to 0.11 kWh m^{-3} not implying significant reductions in yield, just setting the pressure head in 33 m. Under this conditions, the profit in the critical field is 1,080.00 € ha^{-1}, 25.90 € ha^{-1} more than the current condition.

A good election of emitters in the critical fields is essential to ensure an optimum performance of the irrigation system. Pressure compensating emitters reduce the impacts of the oscillations in pressure head and minimize the impacts on yields.

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Table 1. Relations of the pressure head at the pumping station, average hydrant pressure, irrigation uniformity (σ_e, CV_e, CU_c) and yield in the critical field.

Pressure head (m)	$\overline{h_c}$ **(m)**	σ_e	CV_e **(%)**	CU_c **(%)**	**Yield (%)**	**Energy consumption per unit of irrigation water supplied (kWh m^{-3})**
55	41.25	1.11	0.22	99.82	92.1	0.19
53	39.24	1.11	0.22	99.82	92.1	0.18
51	37.25	1.11	0.22	99.82	92.1	0.17
49	35.26	1.11	0.22	99.82	92.1	0.17
47	33.25	1.15	0.23	99.82	91.9	0.16
45	31.25	1.20	0.24	99.81	91.7	0.15
43	29.25	1.69	0.34	99.73	90.7	0.15
41	27.25	1.83	0.37	99.71	90.3	0.14
39	25.25	1.99	0.40	99.68	89.9	0.13
37	23.24	2.18	0.44	99.65	89.4	0.13
35	21.25	2.40	0.49	99.61	88.8	0.12
33	19.25	2.67	0.55	99.56	88.3	0.11
31	17.25	2.98	0.62	99.51	87.6	0.11
29	15.25	4.65	0.98	99.22	86.1	0.10
27	13.25	5.95	1.27	98.99	84.8	0.09
25	11.25	11.31	2.47	98.03	82.3	0.09

Table 2. Profit of the critical field.

Pressure head (m)	$\overline{h_c}$ (m)	Yield (%)	Y_c (kg ha^{-1})	P_c (€ kg^{-1})	C_w (€ m^{-3})	C_w (€ ha^{-1})	Profit (€ ha^{-1})
49	35.26	92.1	9,531	0.14	0.017	311.21	1,023.13
45	31.25	91.7	9,489	0.14	0.015	274.36	1,054.10
33	19.25	88.3	9,137	0.14	0.011	199.12	1,080.06

Table 3. Average hydrant pressure, standard deviation (σ_e), CV_e, CU_c and yield for the Scenarios A and B.

	Scenario A					Scenario B				
Pressure head (m)	$\overline{h_c}$ (m)	σ_e	CV_e (%)	CU_c (%)	Yield (%)	$\overline{h_c}$ (m)	σ_e	CV_e (%)	CU_c (%)	Yield (%)
33	19.25	44.07	8.13	93.51	100	19.24	50.11	9.16	92.69	100
31	17.25	46.72	9.37	92.52	90.9	17.25	52.33	10.50	91.62	90.9
29	15.24	50.46	11.21	91.06	80.7	15.25	55.56	12.47	90.05	79.7
27	13.25	56.13	14.17	88.70	69.2	13.25	60.51	15.62	87.54	67.3
25	11.25	66.07	19.85	84.16	55.7	11.25	69.44	21.69	82.69	53.0
23	9.25	115.53	47.01	62.49	37.2	9.25	109.35	46.85	62.62	34.6

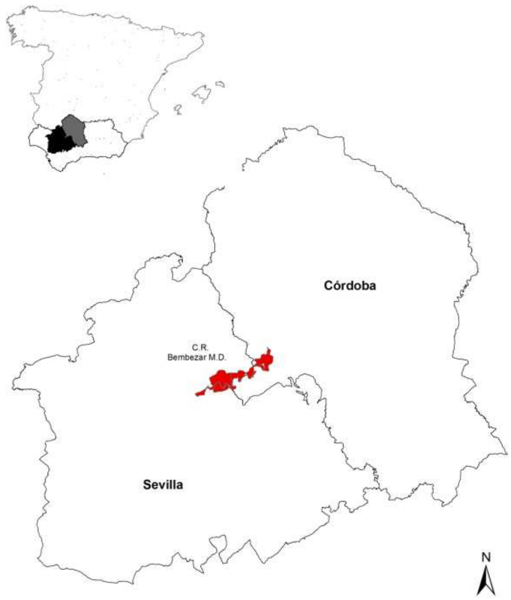


Figure 1. Location of Bembézar M.D. irrigation district, Spain.

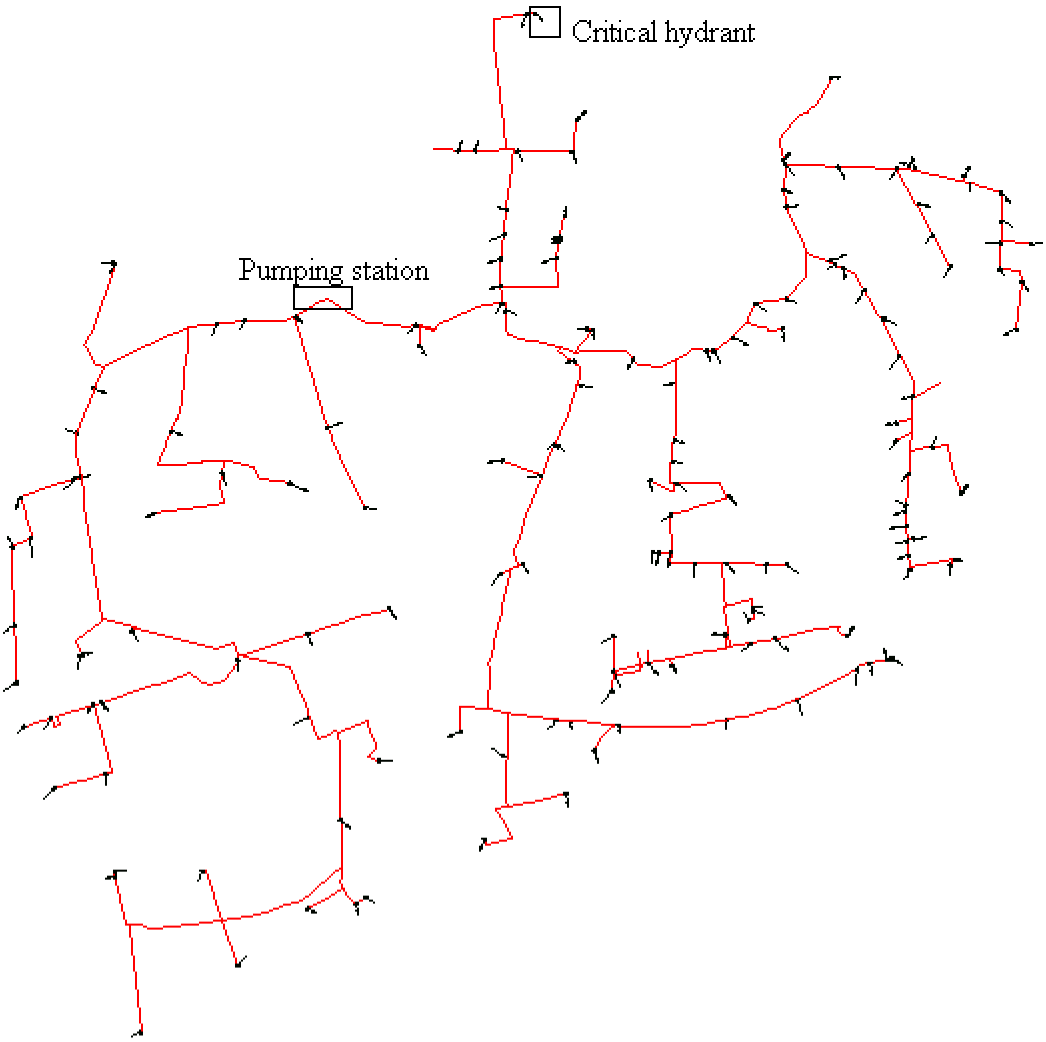


Figure 2. Distribution network and location of the critical hydrant.

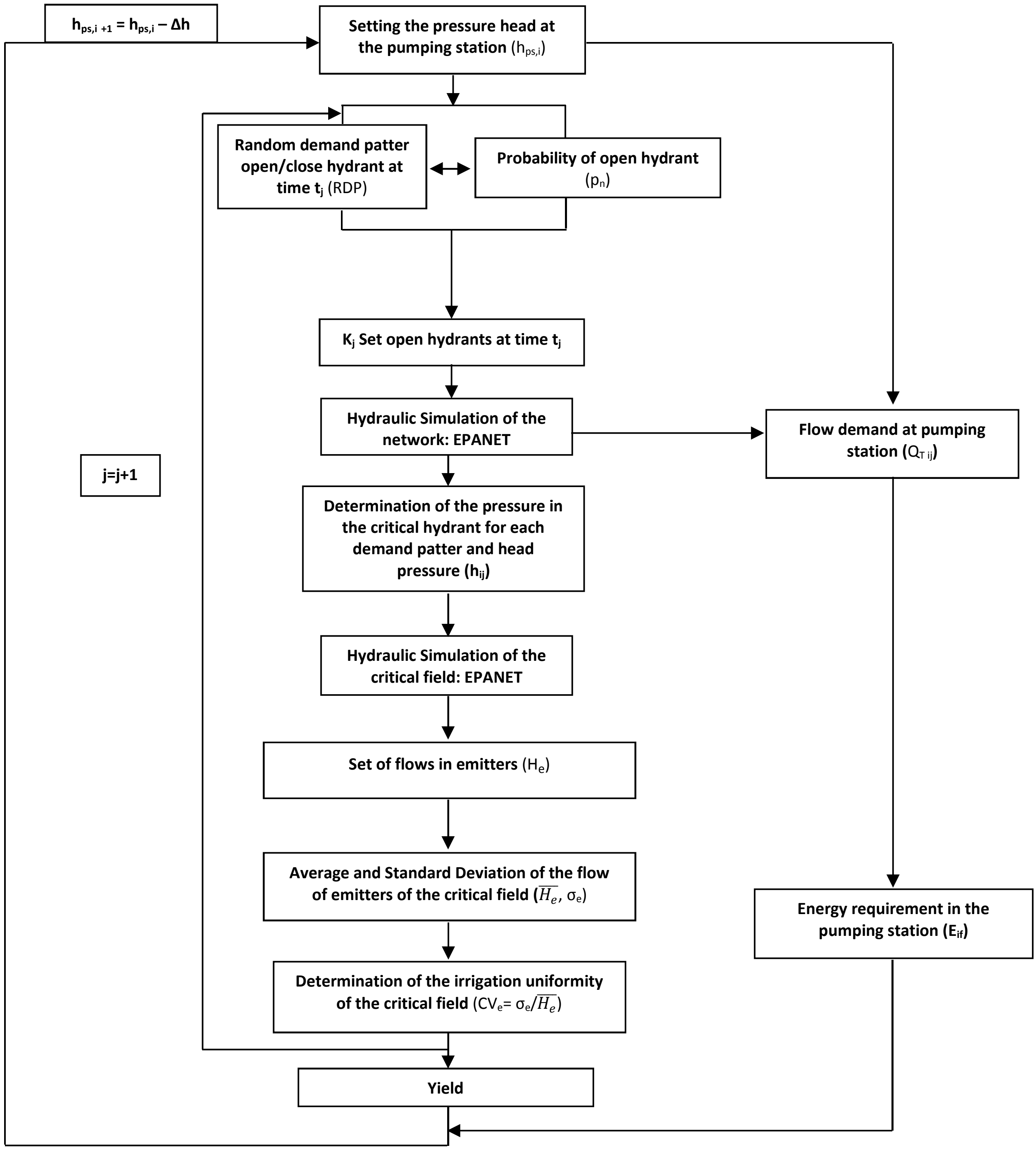


Figure 3. Schematic representation of critical field evaluation model.

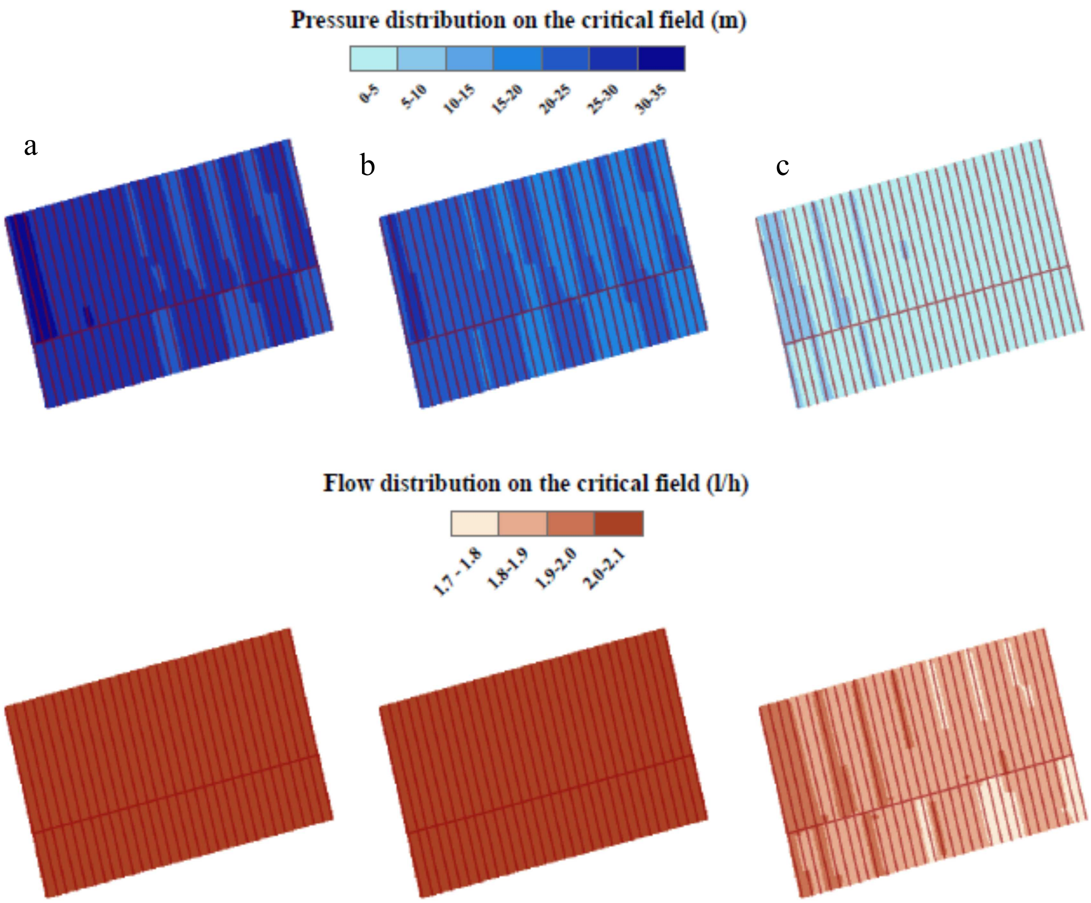


Figure 4. Spatial distribution of pressure and flow in the critical field for (a) 53 m (b) 43 m and (c) 25 m of pressure head at the pumping station.

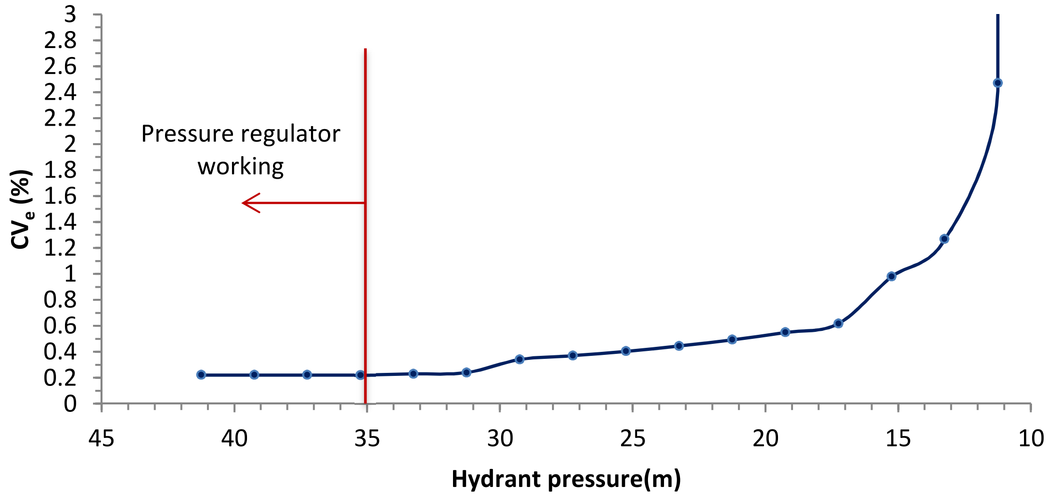


Figure 5. Relation between pressure at hydrant and the irrigation system's CV.

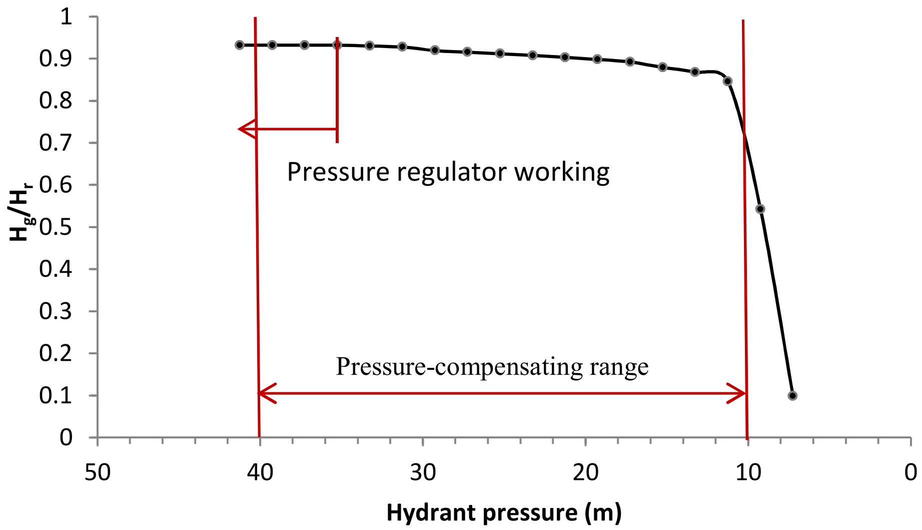


Figure 6. Relationship between — and pressure at hydrant.

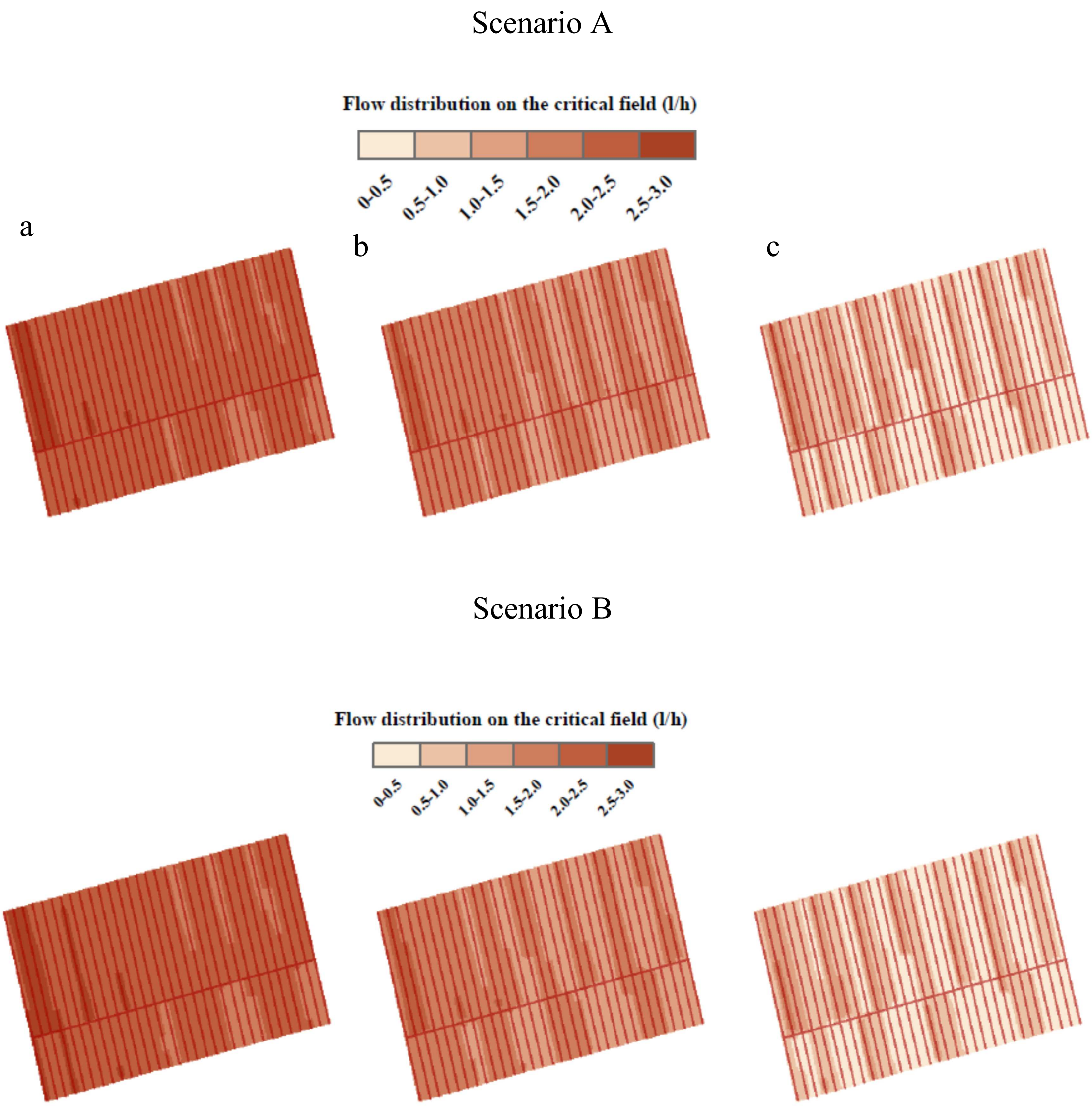
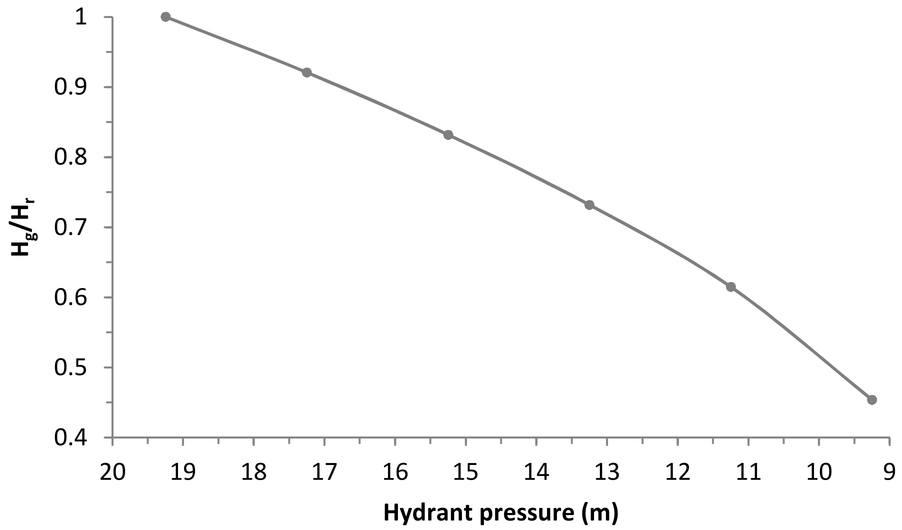


Figure 7. Spatial flow distribution of the non-compensating emitters in the critical field in the scenarios A and B for 33 (a), 27 (b) and 21 (c) m, respectively, of pressure at the pumping station.

Scenario A



Scenario B

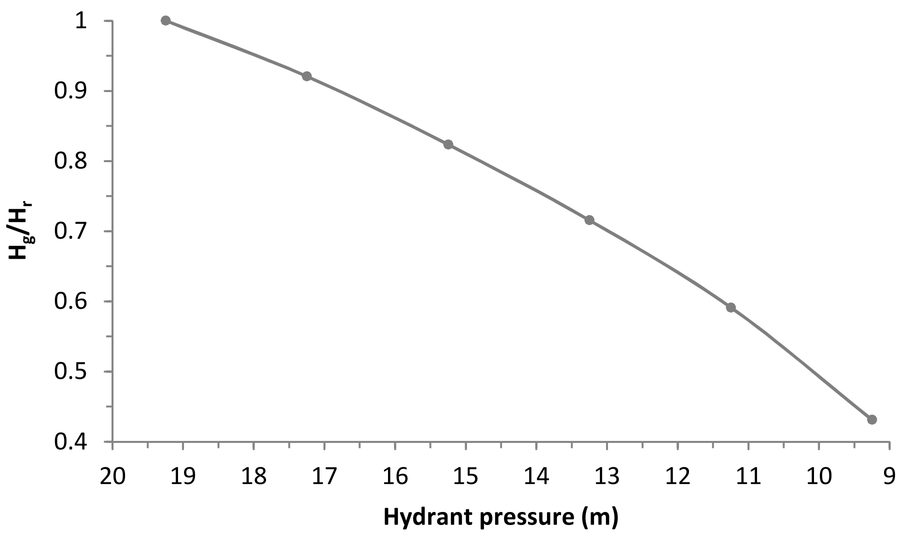


Figure 8. Relationship between $\frac{H_g}{H_r}$ and hydrant pressure in scenarios B and C.

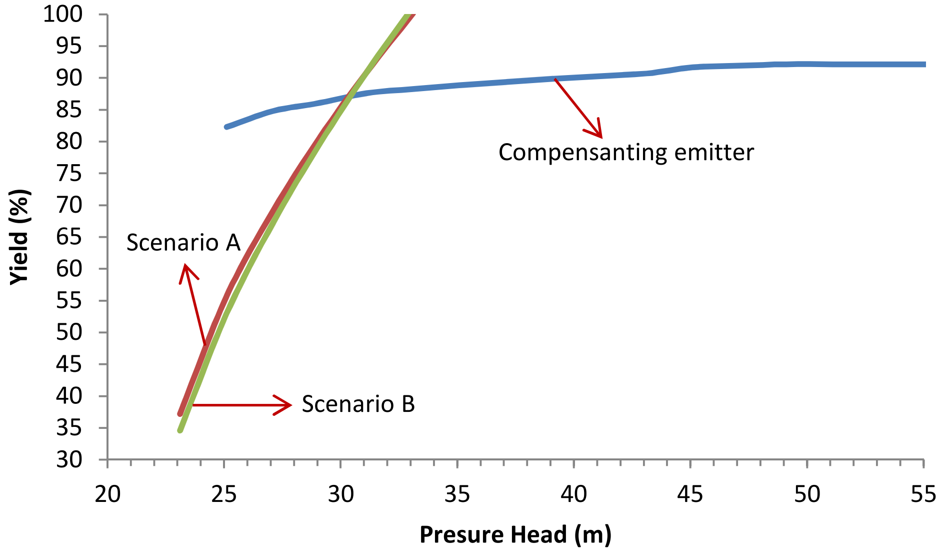


Figure 9. Relationship between yield of all the emitters and pressure head (m).